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Unified optimization of intelligent home appliances with a cost-effective energy management system

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Abstract:

The scheduling in smart houses is a pivotal concern in power consumption networks on the demand side owing to the expanding usage of renewable energy resources (RERs). To address the issue of distributed energy management raised due to the expanded use of RERs, a peak-limiting distributed-time-bound strategy is proposed and executed, providing a flexible distribution for the scheduling of appliances under real-time and time-of-use pricing schemes. This paper presents a case study based on the pilot project initiated in Gujarat, India, to better understand the scenario. The current work engenders a smart home energy management system harmonizing with a residential grid. By embracing the proposed methodology, the electricity cost can be curtailed to the bare minimum while concurrently reducing the peak demand, harnessing the maximum potential of renewable energy sources, and optimizing the peak-to-average ratio. Multiple scenarios have been enacted, encompassing various applicable tariff structures, methodologies, and the integration of renewable energy sources. The electricity bill using the proposed strategy is significantly reduced by about 95.25 % compared to a random scheduling case (base case) considered in the paper. The maximum peak reduction compared to the random scheduling case is about 70.8 % in one of the presented scenarios.

Keywords: Cost-effective energy management; Demand response; Home energy management; Renewable energy source integration; Dynamic pricing; Smart home

1. Introduction

In the era of modernization and development, rising energy demand is a well-known fact [1](4.6% increment in global demand in the year 2021). According to the International Energy Agency, India ranks third in global energy consumption, which has doubled since 2000 as a result of growing living standards. After recovering from the peaks of COVID-19, India is now in a dynamic situation in terms of energy growth. After COVID-19, with the improvement of the Indians' financial situation, a significant percentage of the population is heavily purchasing electrical items for their comfort and transportation. India's growing electric vehicle industry, as well as the increased installation of heating, ventilation, and air conditioning (HVAC) systems as a result of global warming, will require the country to adopt its power infrastructure to accommodate rising energy consumption [2].

It has become crucial to enhance the electricity supply by deploying distributed energy resources (DERs) to bridge the gap between demand and supply [3]. The Indian government has set a target of adding 175 GW of renewable energy capacity by the end of 2022, including 100 GW coming from solar PV, 60 GW from wind power generators, 10 GW from bio-power plants, and 5 GW from small hydro-power plants [4]. India has seen the highest growth of 9.83% in renewable energy in 2022 with 70.10 GW from solar as of July 2023. This case study is based on the data of Gujarat state and the pricing schemes are taken from a report of the India Smart Grid Forum [5]. Uttar Gujarat Vij Company Ltd. has employed smart metering facilities for 22,230 users as a pilot project. Wind power accounts for roughly 6073.07 MW of the total renewable capacity (RC) installed in Gujarat (8651.8 MW), almost 70% of the total RC. Gujarat is currently using a variety of electricity tariffs e. g. , three-part tariffs for residential customers and time-of-day pricing for a few industrial customers. Still, the Ministry of New and Renewable Energy (MNRE) is also working on implementing other dynamic tariffs for peak load duration. Starting from Gujarat, other states can also deploy these tariffs. Depending on the success of the pilot project, the implementation of demand response programs (DRPs) will surely increase throughout the country significantly.

The DRP is an excellent tool [6], [7] for the utility to increase the efficiency of the electricity distribution network [8], to reduce the operational cost [9], and to meet the energy demand by making a flexible load demand. With respect to an industrial customer, a residential customer is significantly affected by the electricity cost, and this can be a motivating factor to make his load adjustable. A customer can also be a prosumer by generating electricity at its end, reducing its electricity consumption bill, and supplying the extra produced electricity to the utility or neighborhood, creating another source of income. The energy consumption by smart houses has increased from 20% in 2018 [10] to around 40 % of the worldwide power [11], which will definitely increase when electric vehicles [12] replace the major portion of conventional vehicles [13]. The ever-increasing power demand will cause unforeseen peaks in the demand generation curve, putting a strain on generation, transmission, and distribution assets. To meet such unanticipated peaks, significant capacity expansion is required. However, during off-peak periods, this peak capacity remains unproductive, causing a loss of the cost of available capacity and efficiency [5].

A DRP enables the use of renewable energy resources (RERs) on the customer's end. Due to the high penetration of RERs on the distribution side, energy management and scheduling have become critical issues [14]. In [13], the authors proposed a hybrid of nature-based optimization techniques for the optimization of the home energy management system (HEMS) model including genetic algorithm (GA), particle swarm optimization (PSO), wind-driven optimization, and other heuristic techniques. It was found that the results were better than the stand alone techniques in terms of execution time and convergence rate. A flat-rate tariff is compared with a day-ahead price tariff, and factors like energy cost, peak-to-average ratio (PAR), and carbon emission are studied. The authors [15] proposed a HEMS including RERs and battery storage using a day-ahead real-time pricing (RTP) plan to schedule the appliances. A hybrid genetic-based harmony search approach was used for modeling the system, which has been shown to be superior to the GA and the harmony search algorithm. However, this algorithm has the drawback of being limited to a small number of users rather than the entire community.

The authors [16] studied Australian grid-connected houses with different solar PV sizes installed under a time-of-use (TOU) pricing scheme. Various energy management solutions for battery discharging durations are discussed. It has been discovered that the combination of DRP with TOU and a battery, might lower the peak load by up to 35%. By comparing the TOU and RTP pricing schemes, the authors in [17] employed a model predictive control technique for domestic-controlled appliances to reduce power costs. The study comprised photovoltaic (PV) panels with batteries for an un interruptible power supply whenever local demands demanded it.

The authors implemented an event-driven approach [18] for the fast reaction of an automated controlling system for any random change in load conditions. Different approaches have been proposed and discussed for the accuracy of the real-time values, which have been decided to implement in the pilot project at AutBudNet laboratory.

The authors [19] used PSO and artificial bee colony optimization methods for the single objective function used to model an HEMS comprising microgrid, PV, wind, and diesel engines. A number of houses with 5 kW loads and EVs were included for microgrid operation. The heuristic methods were compared by operating in autonomous and coordinated modes. The coordinated mode was found superior to the autonomous mode because it covered more factors than when working alone. The authors [20] proposed a management framework for a local energy market having multiple smart homes connected to the grid. The funded project has focused on reducing operation cost, grid dependency, and maximizing revenue. The framework has been compared for three algorithms RAO-1, JAYA, and teaching-learning-based optimization techniques and the JAYA algorithm was found superior to the others.

The authors [21] used a fuzzy interface system to save energy from the HVAC system and use the saved energy to improve the quality of lighting in the house. TOU pricing tariff adopted from HydroOne has been used in the study for incentive purpose during high production. Several scenarios for different visual comfort (illumination) of the user were discussed and accordingly, five membership functions ranging from very low to very high lux were created for each scenario. Although the study has worked on providing a better environment to the people of the building but it was limited to HVAC and lighting only. The authors [22] proposed a transactive energy approach using game theory to solve the conflicts between utility and prospers. The study focused on the secondary distribution network and the transformer life duration by resolving PQ difficulties and voltage unbalance. Their findings show that PQ difficulties can be remedied by reducing the PV output power and the EV charging requirement. The charging and discharging cycle of an EV also plays a major part when it comes to the stress of a load on the local transformer; that's why state of charge (SOC) management is also a key point in the energy management of a smart home.

The authors [23] proposed a method to manage the generation and various loads on an all-electric ship for the minimization of greenhouse gas emissions and power operation costs. The objective function in the ship could have a lot of sensitive constraints, which makes it quite complex, which is why dynamic programming was employed to solve it. The authors [24] used Lyapunov optimization to optimize a grid-connected house employed with an HVAC load. The goal of the study was to minimize the average cost and thermal discomfort of the residents. The employed algorithm reduced the overall electricity cost by up to 20.15%, maintaining the comfort constraints required by the resident. However, the effect on the user's comfort during the DRP was not analyzed. The authors [25] formulated a Markov decision process for the scheduling of home appliances to minimize energy cost, but the study was limited to HVAC loads and non-shiftable loads in a smart home.

Research gaps:

i. The presence of a robust infrastructure, such as smart grid systems and advanced metering infrastructure, has facilitated the implementation of demand response programs in Europe. In contrast, the infrastructure in India is still in its early stages of development, which could hinder the implementation of demand response programs. Many researchers have worked on demand response implementation considering several European countries but not India. Research is needed to explore effective ways to engage these stakeholders in India and identify the factors influencing their participation in demand response programs.
ii. Home energy management has been a vast area of research for the last few decades, and many studies are available on optimizing energy costs. The authors [15], [19], [26] have formulated and solved the optimization problems using heuristic methods providing an approximate solution, which may or may not be close to the optimal solution.
iii. Many research papers considered the time horizon divided on an hourly basis, which means, it will be highly distant from real-time because energy prices, demand, and supply change rapidly, so time slots would be more pragmatic.
iv. Human behavior is very difficult to understand, making it very unpredictable; that's why many listed research articles haven't considered the customer's comfort level along with the scheduling of appliances in their works.
Contribution of the paper:
The electricity market design in India is vastly different from that in Europe, and research is needed to understand how demand response programs can be integrated into the existing market structure. This includes exploring the role of different stakeholders, such as utilities, aggregators, and consumers, in the demand response market. This study has focused on a project in India where smart metering is in its pilot state; hence this study can play a crucial role in this area. Mixed integer programming (MIP) solvers are very flexible and can handle a wide range of optimization problems, including problems with complex constraints, non-linearities, and integer variables. This paper uses MIP techniques to solve the objective function, giving the same result every time, providing a global solution, and making the solution more reliable. The major contributions of the proposed work are:
i. In this paper, higher-resolution time slots of fifteen minutes are chosen to provide greater flexibility in scheduling to make the results more realistic.
ii. Customer comfort can be a subjective concept and may vary greatly depending on individual preferences, lifestyle, and cultural norms. It may also be difficult to measure or quantify customer comfort in a way that can be included in research studies. In this paper, a delay factor (DF) has been assigned to schedule the high-priority appliances as soon as possible, so that the user's comfort would not be affected.
iii. In this paper, a peak limiting distributed-time bound strategy (DTBS) is proposed and implemented in which a single appliance is given multiple choices so that a more flexible and flattened load curve can be found.
To the best of the author's knowledge, the proposed strategy has not been implemented in any of the research articles and found effective in terms of PAR and electricity cost, as depicted by results included in section 3. The remaining paper is constructed as follows: Section 2 consists of the details about the details and modelling of appliances and locally available sources. It also describes the pricing tariff employed in the study, the objective function, and the proposed solution for the study. Further, section 3 discusses the case study and analysis of the results of the study. Section 4 summarizes all the major results of the study while section 5 concludes the results including the limitations of the study. In section 6, the nomenclature is available for the undefined symbols.

2. System modelling

The study centers on residential consumers equipped with smart meters and in-home displays, enabling them to actively engage in demand response programs by monitoring dynamic pricing schemes, prioritizing energy usage based on personal preferences, and accessing real-time prices and consumption data. The appliances employed in the house are supposed to be engaged with an intelligent controller that can communicate and operate the devices according to the given operating instructions.
The set of appliances A=1,2,.......20 employed in a group of N houses is supposed to be controlled by a home energy management center (HEMC). The HEMC will find the time schedule for each appliance of each house. For more realistic behaviour, the time horizon of 24 hours is divided into 96 slots of 15 minutes each, denoted by H 1,2,.....96. The energy consumed in any time slot h ∈ H by the appliances a ∈ A for each house n ∈ N is denoted by a set $Q_{n,a}$.

$$\mathrm{Q_{n,a}} = [\mathrm{Q^{1}_{n,a}}, \mathrm{Q^{2}_{n,a}} \ldots\ldots\ldots\ldots \mathrm{Q^{h}_{n,a}}] \tag{1}$$

The total energy consumed by an appliance in a complete time horizon is denoted by $W_{n,a}$ can be written as

$$\sum_{h\in H} \mathrm{Q^{h}_{n,a}} = \mathrm{W_{n,a}} \qquad \forall n, \forall a \tag{2}$$

From the utility perspective, peak demand per slot should be within a specified limit so that the need for peak power reserve generators gets reduced, which further helps in the reduction of the extra burden on the utility during peak hours. Keeping it in mind, a constraint is used that limits energy consumption in any slot

$$\sum_{n\in N} \sum_{a\in A} \mathrm{Q}^{h}_{\mathrm{n,a}} \leq \mathrm{W_{max}} \qquad \forall h \tag{3}$$

To overcome the issue of limited kinds of appliances found in many works of literature, twenty appliances are included in the study, covering almost all sorts of residential loads, divided into four categories according to their operating characteristics [27], as shown in Table 2
Interruptible loads (Type-1): This category includes appliances that can run at any time slot selected by the user, and that can be turned OFF and restarted at any time slot. These appliances can operate in ON (1) and OFF (0) states depending on the binary variable $y_{h,n,a}$ consuming a fixed level of

energy $Y_{n,a}^{max}$ and $Y_{n,a}^{min}$ respectively. The energy consumption for such loads is written as

$$Q_{n,a}^{h} = y_{h,n,a} * Y_{n,a}^{max} + (1 - y_{h,n,a}) * Y_{n,a}^{min} \quad \forall h \tag{4}$$

Considering $T_{n,a}$ as the total operating duration of an appliance, and the customer's preferred slots arranged in a vector $S_{h,n,a}$ (value is 1 during operation and 0 otherwise), the operation of interruptible loads is controlled by

$$\sum_{h \in H} (y_{h,n,a} * S_{h,n,a}) = T_{n,a} \tag{5}$$

Uninterruptible loads (Type-2): Unlike the interruptible ones, these appliances can not be turned off in between the given tasks. The HEMC will decide the starting time only. For this category, HEMC will decide a single time schedule from the user's preferred time slots according to the operating duration of the appliance.
Plug-in Hybrid Electric Vehicle (PHEV): It is a special type (*Type-3*) of load that acts like a load as well as a distributed energy source depending on its SOC. The minimum and maximum limits constrain the total energy consumed by these appliances.
Must-run loads *(Type-4):* This category includes the HVAC and lighting loads of the residence.

$$Q_{n,a}^{h} * S_{h,a} = W_{n,a} \quad \forall h, \forall n \tag{6}$$

The energy consumption by all the appliances must be bounded to certain limits, such as

$$Y_{n,a}^{min} \leq Q_{n,a}^{h} * S_{h,n,a} \leq Y_{n,a}^{max} \tag{7}$$

2.1 Pricing schemes

Dynamic tariff architectures carry the ability to flat the demand profiles, allowing power companies to save money on capacity expansion while also planning energy generation and distribution more efficiently. For implementing a DRP, the load should be adjustable so that end-use consumers can vary their electricity usage from their usual or current consumption behaviour, responding to market signals enabled by dynamic tariffs. The load is controlled either directly by the utility or the user's end itself, depending on the type of DRP applied. In this case study, a price-based demand response strategy is employed using TOU and RTP tariff structures which are compared with the fixed rate tariff as a base case.
In the TOU pricing scheme, the electricity tariff for the time horizon of a day is usually divided into 3 or 4 zones, depending on the average load on the grid and prices in the power market. The TOU rates used in this study are shown in Table 1, which are taken from the Indian Smart Grid Forum report [5]. In the RTP scheme, rates might vary in a few minutes or on an hourly basis, but for more realistic results, 15-minute slots are considered in this study, and prices for Gujarat are taken for the Indian electricity market from the Indian Energy Exchange [28] shown in Fig. 1.

2.2 Wind generator

Gujarat is a coastal area, which is why it has massive potential for wind power generation, as stated in the introduction section (70% of the total RC is from wind generators). In this study, a 5 kW wind generator is supposed to be installed on the occupant's premises, and the total generated power is shown in Fig. 2. The wind speed data, equations, and the wind power generated are taken from [27] and [29].

2.3 Problem formulation

The modelled final objective function has two parts programmed to minimize the overall electricity bill the user has to pay and maximize the occupant's comfort level. The HEMC will schedule the interruptible appliances in the most economical time slots and uninterruptable appliances into the time schedule that the DRP participants prefer.
The total bill waved on the customers is formulated as

$$Q1 = \sum_{h} (\sum_{n} \sum_{a} Q_{n,a}^{h}) * C_{h} \tag{8}$$

The symbol C_h denotes the price of the electricity consumption in the particular time slot 'h' according to the tariff accepted by the customer.
Now it is evident that in this era where several appliances are to make life easier and more comfortable, any modern customer would want to maximize his comfort by utilizing his appliances during his preferred time duration as soon as possible. For this, some appliances have been given higher priority and a linear delay factor (DF) $F_{n,a}^{h}$ has been included starting from 1 at the first preferred slot with an increment of 25% per slot till the last slot. To apply this factor to the scheduling, a comfort cost (Q2) has been calculated according to the energy utilized and written as

$$Q2 = \sum_{n} \sum_{h} \sum_{a} (Q_{n,a}^{h} * F_{n,a}^{h}) \tag{9}$$

High-power appliances have a significant portion of the electricity bill, and hence, this comfort cost is associated with $Q_{n,a}^{h}$ so that high energy-consuming appliances will be shifted first, and the overall cost will be optimal. This term will undoubtedly increase the electricity bill, but it will schedule the high-priority appliances as soon as possible.
By considering both terms, the final objective function will act as a multi-objective function by scheduling the appliances for minimum electricity cost as well as comfort cost and can be written as

$$Obj = \min\{\sum_{h} (\sum_{n} \sum_{a} Q_{n,a}^{h}) * C_{h} + \sum_{n} \sum_{h} \sum_{a} (Q_{n,a}^{h} * F_{n}^{h})\} \tag{10}$$

2.4 Inclusion of wind generators

The main advantage of DRP is the ability to integrate distribution generators by the occupants at the load end and get an opportunity to sell the remaining electricity to the grid. This facility also turns a customer into a producer, and people can earn money if they have a large surplus of extra power. The house should be enabled for work in both grid-to-home (g2h) and home-to-grid (h2g) modes for this facility. In this study, wind power generated by each user, buying price, and selling price to the grid is kept the same for simplicity, but in a practical scenario, it is regulated according to the policy of the government bodies. By including the wind-generated power, the objective function can be modified as

$$\mathrm{Obj} = \min\{\sum_{h}(\sum_{n}\sum_{a} Q^{h}_{n,a} - P^{h}_{w,n})) * C_{h} + \sum_{n}\sum_{h}\sum_{a}(Q^{h}_{n,a} * F^{h}_{n})\} \quad (11)$$

Here $P^h_{w,n}$ is the wind power generated by the nth occupant at h_{th} time slot. This study focuses on the on-grid operation; hence, battery energy storage system is not included to overcome the uncertainty in wind power.

2.5 Proposed solution

The objective functions of the paper are shown as 10 and 11, which are linear and constrained with 2 to 9. Some constraints are integers, and some are binary in nature, making the problem linear and solvable using the MIP technique. In the upcoming sections, different scenarios are discussed for which suitable solvers like CPLEX and DICPOT are used to solve the problems [30]. The branch and cut algorithm is used by the CPLEX solver of GAMS, which is a very efficient and successful tool for solving these types of problems and provides a global solution every time we run the program, unlike heuristic methods that offer a locally optimal solution [31]. Fig. 3 shows the flowchart for the proposed strategy for optimal scheduling of the home appliances. The set vectors S1, S2 & S3 mentioned in Fig. 3 are the different time sets (Set 1, Set 2 & Set 3) used to implement the proposed distributed-time bound strategy as shown in Table
reft2 in the next section. Further, S1, S2 & S3 are explained in detail under subsection "Distributed-time bound strategy". The problem is solved using the CPLEX solver of GAMS software on a 64-bit, Intel Core i5-1035G1 CPU @1.00 GHz processor laptop.

3. Case study and discussion of results

For this study, three residential consumers are considered to have a wind generator of 5 kW. This generated power is equally distributed among the occupants. All residents are supposed to have the appliances [27] listed in Table 2 and agree to participate in the DRP. The type of the appliances is selected according to the operating characteristics as discussed in the section on system modelling. The operating time of appliances is divided into slots of 15 minutes and accordingly, per day consumed energy is also divided according to the load characteristics of that particular appliance.

For this case study, the combined maximum energy consumption of all three customers for a particular time slot is taken as W_{max}=5 kW. Different scenarios have been created to see the effect on scheduling, PAR, cost, and comfort level of the consumer, compared to the base case. The PAR value is calculated from the curve of power drawn from the grid in all scenarios. For the calculation of average power, all 96 slots are included, even if there is any null or negative power demand. For the base case to scenario-8, operating time preferences are collected as set-3, whereas in the distributed-time bound strategy, different options are available, as shown in Table 3.

Input Data: Operating characteristics of the appliances, users' preferred slots in different scenarios, maximum and minimum limits of the energy consumed by the appliances, maximum energy that can be transferred to the grid, electricity rates in different tariffs, wind power derived from the wind speed data, are considered as inputs where required.

Base case: In the base case, customers randomly schedule their appliances but within the same preferred time slots, which are later offered for DRP. It is assumed that all three customers are selecting the same duration for a similar type of appliance, and a fixed tariff of 6 INR is applied for electricity consumption. Since the data is in the form of power per slot, it reflects the combined energy consumption for all the users, and Fig. 4 shows the random scheduling for the base case without any DRP.

It is clearly seen in Fig. 4 that the maximum demand is 9.0223 kW at the 29^{th} slot, whereas the average of the load curve is found to be 1.5306 kW, and thus PAR is calculated as 5.8945. This high peak can cause immense stress on the power system, and reserve cost is also high since the service provider has to purchase the peak load generator for such a small operating duration. The total energy cost is calculated to be 293.88 INR per user and a total of 881.64 INR.

Now, in order to integrate DRP, a dynamic pricing mechanism must be established, allowing loads to be transferred to low-cost time slots. In this study, RTP and TOU tariff is implemented, as shown in upcoming scenarios. Although all of the scenarios assess the occupant's comfort level by taking into account his choices, each situation has its own set of inclusions and exclusions.

Scenario 1: Scheduling of the appliances with RTP tariff structure.

In this case, an RTP tariff is applied to integrate DRP, and scheduling is done to reduce the peak power demand. Since separate scheduling of 20 appliances for each user will be complex to show in a figure hence aggregated scheduling and load curve for each user is shown in Fig. 5. A segment is focused on the graph, in which it is evident that HEMC has attempted to manage each user with a separate operating time in the user's preferred time slots. Despite providing only a few extra slots other than required for each appliance's operation, the load has been flexible enough to provide a flattened load curve. The cumulative peak power has been decreased to 4.927 kW, a 45.39 percent drop from the base case's 9.0223 kW, and PAR is also reduced from 5.8945 to 3.219. As a result, the utility's need for peak load generators is significantly lowered.

Since each user's load curve is different, different peaks and PARs are noticed. The peak power demand for users 1&3 is 4.302 kW, while for user 2 is 4.596 kW. The total cost of electricity for all consumers is determined to be 658.22 INR.

Scenario 2: Scheduling of the appliances with RTP tariff structure considering DF.

Eight appliances of each occupant's choice have been prioritized more than other appliances. The purpose of the priority is to start a particular appliance as soon as possible in the desired time schedule. Personal Computer, Water Pump set, Coffee Maker, Range Top, Microwave Oven, Toaster, Toaster Oven, and Oven are supposed to high high-priority appliances. A linear DF is designed to start these high-priority appliances as soon as possible. Under scenario 1, for user 1, the water pump was scheduled in 85^{th} to 96^{th} slots while the available slots were 77^{th} to 88^{th}. Due to this DF, the water pump is rescheduled to 77^{th} to 88^{th} slot, shifting toward minimum delay. Similarly, the toaster is shifted toward the 29^{th} slot from the 30^{th} slot, and the toaster oven is shifted from the 87^{th} slot to the 81^{st} slot. To show all the variations in a graph is not possible here, but the effect of the DF on the shifting of loads can be seen in Fig. 6.

Separate load curves for each user are shown in Fig. 7, where rescheduling can be clearly seen in the zoomed-in section.

The overall load curve's peak demand is decreased to 4.7848 kW with a PAR of 3.126, a 46.97% reduction compared to the base case and 2.89 % compared to scenario 1. PAR in this scenario is found to be 3.126, which means that stress on the power network and utility capital investment is far reduced. The customer's comfort level is increased as his appliances started the instant when he requested them, but the occupier is charged an additional fee due to the redeployment. The combined electricity bill of all users is increased to 670.44 INR. An extra cost termed as comfort cost in (9) is calculated to be 65.34 INR, and thus overall energy cost paid by the consumer is 735.79 INR.

Scenario 3: Scheduling of home appliances with the inclusion of wind generator while implementing RTP with DF in the grid to home (g2h) mode.

A small wind generator of 5 kW is supposed to be used equally by all three users, and wind energy is supposed to be free of cost for all users. In this scenario, it is considered that power transfer between houses and the grid is one-way, i.e., grid to houses only. Because wind energy is available for all consumers' household appliances, there are numerous periods when energy demand from the grid is zero and energy is supplied solely by the wind. For this scenario, power demand from the grid is shown in Fig. 8. In the previous scenario, the aggregate power consumption, which was 145.94 kW, has now decreased to 66.95 kW.

The costs of energy usage for users 1, 2, and 3 are 99.97 INR, 99.97 INR, and 109.37 INR respectively. The total cost of electricity for all customers is estimated to be 309.31 INR. The total amount paid to the utility is estimated as 385.08 INR after including the comfort cost of 75.76 INR.

Scenario 4: Scheduling of home appliances with the inclusion of wind generator while implementing RTP with the grid to home (g2h) mode and home to grid (h2g) mode. For the full utilization of RE sources and the benefit of the occupant, bidirectional power flow should be enabled so that customers can sell the extra power to the grid. This study has exercised the purchasing and selling prices equally; however, they may fluctuate depending on utility tariffs. This enabling of bidirectional energy flow changed appliance scheduling as shown in Fig. 8 to Fig. 9. The negative power in Fig. 9 shows the energy fed back to the grid. Although the appliances' ratings and operational characteristics, as well as the wind energy profile for each user, are all the same, the scheduling for each user is distinct. This difference is due to the peak limiting strategy applied in the DRP.

The individual power drawn from the grid by each user is found to be 6.136 kW which is combinedly 18.407 kW. For the same power drawn from the grid, users have to pay different bills, i.e., user 1 has to pay 36.5 INR, and users 2&3 have to pay 30.90 INR due to different appliance scheduling. Thus, the combined electricity bill for the users is found to be 98.32 INR, which is added to the extra comfort cost of 65.34 INR. Hence users have to pay a total of 163.66 INR to the utility, which is about an 81.43% cost reduction compared to the cost of the base case electricity bill. The aggregate peak demand from the grid is found to be 4.62 kW in this scenario, which is a 48.8% drop from the base case and the lowest among the above-mentioned scenarios. The comparative analysis of the final load curves from the base case up to scenario 4 can be seen in Fig. 10, in which peak demand reduction is clearly visible.

Scenario 5: Scheduling of the appliances with TOU tariff structure.

The cases from scenarios 1-4 are now implemented with a TOU tariff proposed for Gujarat, and the scheduling done by HEMC by keeping all other parameters as same, are presented in scenarios 5^{th} to 8^{th}. Load curves for the users after implementing the TOU tariff are shown in Fig. **??**. The combined electricity bill in this scenario is found to be 607.39 INR. Peak demand for the combined load curve is found to be 4.88 kW with an average of 1.53 kW; thus, PAR is calculated as 3.191.

Scenario 6: Scheduling of the appliances with TOU tariff structure considering DF.

The effect of the DF can be easily seen in the zoomed section of the graph shown in Fig. **??**. Regardless of the higher rates at the 77^{th} slot, the water pump must be scheduled there, whereas, in scenario 5, it was primarily running in the 87^{th} – 96^{th} slots during off-peak hours. Due to this type of shifting, the electricity bill has to be increased, excluding the extra comfort cost. In this scenario, the overall consumption bill is calculated as 686.67 INR, including 63.48 INR as comfort cost.

Now, scenarios 7^{th} & 8^{th} are just like 3^{rd} & 4^{th}; the only difference is the applied tariff. Each plot is not exhibited due to the similarity of the processes; however, these cases will be addressed in the conclusion section. All the primary cases (scenarios 1- 4) are considered with distributed time-sets integrated with RTP and TOU pricing schemes in the upcoming scenarios.

3.1 Distributed-time bound strategy

It is the proposed slot preference technique in which distributed-time bounds are introduced to give users more than one choice to operate their appliances. Users are prompted to choose three time sets to implement this approach, which are organized as set 1 (S1), set 2 (S2) and set 3 (S3), as shown in Table 2. In this way, this strategy will give an extra degree of freedom for scheduling the appliances compared to a single time-restricted strategy. In general, the choice of the time slots may be the same or different for similar appliances under a time set for each user. However, in the current work, for simplicity, it is assumed that each user is given the same time slots for similar appliances under a time set. In this study, it is also considered that an appliance of type 1, 3 & 4 can operate only in a single time set e.g., either set 1 or set 2 or set 3. However, the uninterruptable appliances (S. no. 5 - 15) under type-2 have been granted the freedom to operate in different sets, e.g., one appliance in set 1 and another in set 2 or set 3. Although the final allocated set for the complete operation of a single type-2 appliance shall be only one. This means an appliance can't perform half of its task in set 1 and another half in set 2 or set 3. The HEMC will schedule the appliances in each time-set according to the user's choice and choose the best time set (Sm). Based on this, the nomenclature of scenarios from 9_S1 to 16_S3 is done i.e., scenarios 9_S1, 9_S2 & 9_S3 represent that the scheduling of appliances of types 1, 3 & 4 will be done only in S1, S2 & S3, respectively and of type 2 will be done in either of the three sets for each user with all the considered conditions of the scenario 9. Finally, the HEMC will choose the best time set among 9_S1, 9_S2 & 9_S3.

Scenario 9: Scheduling of the appliances with RTP tariff structure under distributed-time bound strategy.

Unlike scenario 1, this scenario has been modified to allow greater flexibility in DRP, giving additional options to operate the appliances, as mentioned under the heading of distributed-time bound strategy. After scheduling, the total bill paid by the customer in scenario 9 is found to be 599.19 INR for time vectors set-1 (S1), 591.44 INR for set-2 (S2), and for the set-3 (S3) bill is found to be 578.39 INR. Hence, in scenario 9 the appliances categorized under type-1, 3 & 4 are finally scheduled according to the time vector set-3 (S3) considering the minimum electricity bill for the users. The combined load curve for scheduling according to the time vector set-3 is shown in Fig. **??**.

It is clearly observed in Fig. **??** that the maximum demand from the grid is 4.877 kW with an average of 1.53 kW; hence, PAR is calculated as 3.186. For a clear understanding of the effect of the distributed-time bound strategy, a comparison of different parameters obtained from scenario 1^{st} and scenario 9_S3 with the base case is shown in Fig. **??**. It is clearly visible from Fig. **??** that in every aspect, the DTBS performs better.

Scenario 10: A DF has been included for early scheduling of high-priority appliances, as in scenarios 2nd and 6th.

While evaluating the results, another intriguing variance is discovered, as shown in Table 4. All of the scenarios are selected to operate in time vector set-3; however, type-2 appliances in scenarios 9 and 10 had the option to run in other sets as well, but due to the minimum cost found in set S3, it was chosen by HEMC. In each scenario highlighted in Table 4, the operating slots for the appliances 7^{th} and 15^{th} are different. In scenarios 9_S3 and 10_S3, type-2 appliances are scheduled in set-1 (S1) and set-2 (S2), respectively, despite having the option to schedule in set-3 (S3) itself.

Similarly, other scenarios displayed in Table 4 have been tested for their operating time, peak demand, PAR, and other parameters, but due to limited space, all plots cannot be displayed.

Scenario 16: Scheduling of home appliances with DF and wind power in g2h and h2g mode.

This scenario is also based on the DTBS with a TOU tariff and bidirectional power flow between houses and the grid. The scheduling of type 1, 3& 4 appliances in S3 yielded the lowest electricity cost among the three-time vectors. Users have the same overall power usage in this scenario, but their appliances are scheduled in different time slots, resulting in a more flattened load curve. This resulted in a reduction in peak load for each customer, as well as a reduction in overall power drawn from the grid due to impaired scheduling. Power consumption by each appliance, available wind power, and grid power used by the user 1^{st} can be seen in Fig. **??**. Due to the availability of distributed slots, it was possible to schedule appliances in the slots where wind power was available and could fulfill all the constraints also. As seen in Fig. 16, wind power is supplied back to the grid at higher rates during peak load times due to enabling bidirectional power flow and an objective function meant to reduce electricity costs. Due to this enabling, the combined electricity cost by three users is found to be negative, i.e., '-6.84 INR', which means the utility will pay the users. Although there is an additional comfort fee of 62.36 INR, bringing the total bill to 41.82 INR, it can be observed that the overall electricity bill decreases significantly from the base case to scenario 16.

4. Result summary

Some key parameters and outcomes of the objective function are presented in Table 5 for a comparative analysis of all the scenarios and to visualize a summarized picture of the study. The rows with the same colour in Table 5 depict the scenarios with all similar conditions except the preference techniques used for different slot selections in the scenarios. For example, in scenarios 1^{st} and 9^{th}, RTP and wind energy sources are used; however, in scenario 1^{st}, a single time-restricted strategy is applied. In scenario 9^{th} proposed DTBS is applied as users' preference technique.

It has been found that the total electricity consumption cost (Q) in the base case, i.e., the random scenario is 881.6 INR. On implementing the RTP tariff in scenario 4, the cost has been reduced to 81.4 percent compared to the base case and found to be 163.7 INR. Similarly, with the TOU tariff in scenario 8, the total cost has been reduced to 86.74 % compared to the base case and found to be 116.9 INR. Among all the tested scenarios, the minimum electricity cost paid to the utility is found in scenario 16 with time set (S3) and calculated as 41.8 INR, which is a significant reduction of about 95.25 percent compared to the base case and hence fulfills the objective of the problem formulated. Enabling the bidirectional power flow is beneficial for achieving maximum output from renewable energy sources. While comparing the two strategies in scenarios 8^{th} and 16^{th}, it can be concluded from the results that DTBS provides a 64.22 percent cost reduction compared to a single restricted time-set approach with the inclusion of RER. This comparative cost reduction can be observed in all related scenarios in Table 5. This significant reduction in electricity prices may encourage customers to participate in DRP and ensure its successful implementation. Finally, it can be commented by analyzing all the results that the TOU tariff structure will prove to be a milestone in Gujarat's power distribution sector for the benefit of utility and customers both because electricity bill is found to be minimum in the case of TOU. In the base case, the peak of 9.02 kW has been found with an average of 1.53 kW; thus, PAR has been calculated 5.89. By successfully implementing the peak limiting strategy, peak demand has been limited to 5 kW. Table 5 shows that the minimal peak of value 2.64 kW has been achieved in scenario 15_S2, which is reduced by 70.8 percent from the base case. It has been found that the wind energy source has been maximum utilized in scenario 16. Different energy costs, peak demands, and PAR have been achieved in scenarios 16_S1, 16_S2 & 16_S3. Now the selection of the optimized set depends on the set priority of these parameters based on the agreement between the utility and the users. In this work, minimization of electricity consumption bill was the priority; hence, 16_S3 has been selected for scheduling purpose by the HEMC.

A conflict has been found in the results of PAR, i.e., a higher value of PAR is achieved in the scenarios in which bidirectional power flow (h2g mode) was enabled, e.g., scenario 16_S3, where the PAR value is found as 22.26. Scenario 16 is a modified version of scenario 5 in a manner by inclusion of h2g mode and DTBS strategy. The peak demand in scenario 5 was found to be 4.88 kW, average 1.53 kW and thus PAR was calculated as 3.19. However, the peak power in 16_S3 was reduced to 4.27 kW by enabling h2g mode compared to scenario 5; but the reduction in average power drawn from the grid is 0.19 kW, which is a significant drop compared to scenario 5, hence, giving a higher PAR value in all scenarios having h2g mode. Further, there are numerous slots in the scenarios with h2g mode where no power is drawn from the grid leading to reduced average power drawn from the grid and therefore increasing the PAR value compared to the scenarios without h2g mode.

5. Conclusion

The paper is focused on the issue of management of RERs and household loads in a distributed network. To get a more flexible and efficient load distribution, a DTBS has been proposed. The main purpose of the proposed strategy was to give more freedom to the occupant by giving multiple choices for operating its appliances. On the implication of the proposed strategy, the HEMC scheduled the appliances and local sources to reduce the peak demand, overall electricity cost and customers' discomfort. The scheduling has been done with the support of RTP and TOU-type pricing DRP. Various scenarios have been presented in the case study by including different pricing schemes and inclusion of sources. In the base case, no wind source has been considered and the customers have opted for a typical self-scheduling; which caused the overall electricity bill to be 881.6 INR. In other scenarios, DF, wind generator, and the DTBS strategy have been included with different pricing tariffs. The effect of bidirectional power flow of households has also been included in scenarios 4, 8, 12 and 16. Considering scenarios 12_S3 and 16_S3 as the final scenarios including all the factors for RTP and TOU pricing respectively, the overall electricity costs were found to be 72.8 INR and 41.8 INR respectively which is nearly 91.74 % and 95.25 % lesser compared to the base case. The effectiveness of the proposed DTBS strategy can be observed by comparing scenarios 8 and 16_S3 since the only difference in both scenarios is the strategy of slot selection. The overall electricity bills in the scenarios were found to be 116.9 INR and 41.8 INR, which is a significant reduction of nearly 64.24 %. Thus, the results clearly showed the effectiveness of the proposed strategy. Although the strategy has shown tremendous potential in reducing the electricity cost but also has some limitations. The proposed strategy will need a heavy and fast controller for fast and complex calculations in case of a large number of users. EV has not been considered in this analysis, although it might be employed in future work to increase the self-utilization of wind power and further reduce the PAR. A forecasting unit can also be used in the future to determine the tariff and weather parameters more accurately which may further result in lower cost.

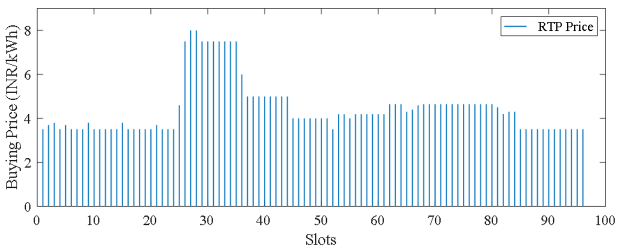

Figure 1. RTP pricing for Gujarat state.

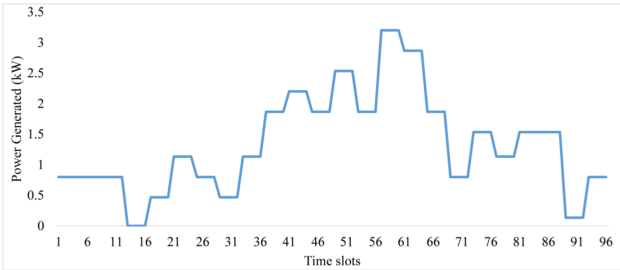

Figure 2. Wind power provided by the wind generator.

6. Nomenclature

Authors contributions
All authors have contributed equally to prepare the paper.

Availability of data and materials
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflict of interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table 1. TOU Pricing.

	Time slots	Buying Price (INR/kWh)
Peak	6 AM-10 AM & 6 PM-10 PM	6.00
Regular	10 AM-6 PM	4.00
Off-peak	10 PM-6 AM	3.00

Table 2. Operating characteristics of the appliances.

S.No	Appliances	Type	Operating Time (minutes)	Slots	Per day consumed energy (kWh)	Set 1	Set 2	Set 3
1	Personal Computer	1	240	16	0.4	6 AM-11AM	4 PM- 9 PM	11AM- 4 PM
2	Television	1	360	24	0.9	10 AM- 6 PM	6 PM- 7 PM & 4 AM- 10 AM	7 PM - 3 AM
3	Water Pump set	1	180	12	2.25	11 AM- 4 PM	4 PM- 7 PM	7 PM- 12 AM
4	Home Vaccum Cleaner	1	120	8	1.48	6 AM- 9 AM	2 PM- 5 PM	9 AM- 1:00 PM
5	Cloth Dryer	2	60	4	5.5	3 PM- 6 PM	12 PM- 2 PM	9 AM - 11 AM
6	Coffee Maker	2	60	4	0.35	12 PM- 2 PM	6 PM- 8 PM	6 AM - 8 AM
7	Range Top (s)	2	60	4	1.6	8 PM- 11 PM	12 PM- 3 PM	8 AM - 12 PM
8	Microwave Oven	2	60	4	0.8	2 PM- 4 PM	5 PM- 7 PM	8 AM - 10 AM
9	Iron Box	2	60	4	1.17	3 PM- 6 PM	8 PM - 10 PM	7 AM - 9 AM
10	Toaster	2	30	2	0.55	5 PM- 7 PM	6 AM - 7 AM	7 AM - 8 AM
11	Toaster Oven	2	30	2	0.75	10 PM-12 AM	6 PM - 8 PM	8 PM - 10 PM
12	Oven Cleaner	2	30	2	1.75	12 AM- 2 AM	8 PM - 10 PM	10 PM –11PM
13	Washing Machine	2	90	6	0.9975	12 PM- 2 PM	8 AM - 10 AM	10 AM -12 PM
14	Dish Washer	2	90	6	1.8	12 AM-2 AM	7 PM - 10 PM	10 PM -12AM
15	Oven	2	90	6	5.25	4 PM-7 PM	9 AM - 12 PM	6 AM - 9 AM
16	PHEV	3	240	16	8.2	12 AM-8 AM & 8 PM-12 AM		
17	AC	4	540	36	9	12 AM-3 AM & 12 PM-4 PM & 10 PM -12 AM		
18	Light	4	660	44	1.9228	6 AM-10 AM & 5 PM-12 AM		
19	Fan	4	900	60	0.9	3 AM-12 PM & 4 PM-10 PM		
20	Fridge	4	All day	96	3.48	All-day		

Table 3. Different scenarios discussed in the study.

Tariff&Slots offered		Single time restricted(Set- S3)	Distributed-time bound(Sets S1 to S3)
Flat		Base Case	
RTP	Without DF and wind power	Scenario 1	Scenario 9
	With DF and without wind power	Scenario 2	Scenario 10
	With DF and wind power in g2h mode	Scenario 3	Scenario 11
	With DF and wind power in g2h and h2g mode	Scenario 4	Scenario 12
TOU	Without DF and wind power	Scenario 5	Scenario 13
	With DF and without wind power	Scenario 6	Scenario 14
	With DF and wind power in g2h mode	Scenario 7	Scenario 15
	With DF and wind power in g2h and h2g mode	Scenario 8	Scenario 16

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Table 4. Scheduling of appliances under different scenarios for user 1.

	Scenarios with scheduled slots for user 1			
Appliance S.No.	Scenario 1_S3	Scenario 2_S3	Scenario 9_S3	Scenario 10_S3
1	45-55,57-61	45-60	45-58 & 60,61	45-60
2	1-12 & 85-96	1-12 & 85-96	1-12 & 85-96	1-12 & 85-96
3	85-96	77-88	85-96	77-88
4	45-52	45-52	45-52	45-52
5	41-44	41-44	52-55 (S2)	52-55 (S2)
6	25-28	25-28	49-52 (S1)	49-52 (S1)
7	45-48	37-40	87-90 (S1)	49-52 (S2)
8	37-40	37-40	57-60 (S1)	57-60 (S1)
9	33-36	33-36	85-88 (S2)	85-88 (S2)
10	30-31	29-30	75-76 (S1)	69-70 (S1)
11	87-88	81-82	95-96 (S1)	89-90 (S1)
12	90-91	91-92	07&08 (S1)	07&08 (S1)
13	43-48	43-48	50-55 (S1)	50-55 (S1)
14	91-96	90-95	91-96 (S3)	91-96 (S3)
15	25-30	26-31	43-48 (S2)	65-70 (S1)
16	1,8,10-12,14, 16-20,23,24,93,94,96	1,8,10-12,14,16-20,23,24, 93-95	10-14,16,17,19, 23,24,89-92,95-96	10-14,16, 17,19, 23,24,89-92,95,96
17	89-96,49-64,1-12	89-96,49-64,1-12	89-96,49-64,1-12	89-96,49-64,1-12
18	25-40,69-96	25-40,69-96	25-40,69-96	25-40,69-96
19	13-48,65-88	13-48,65-88	13-48,65-88	13-48,65-88
20	all	all	all	all

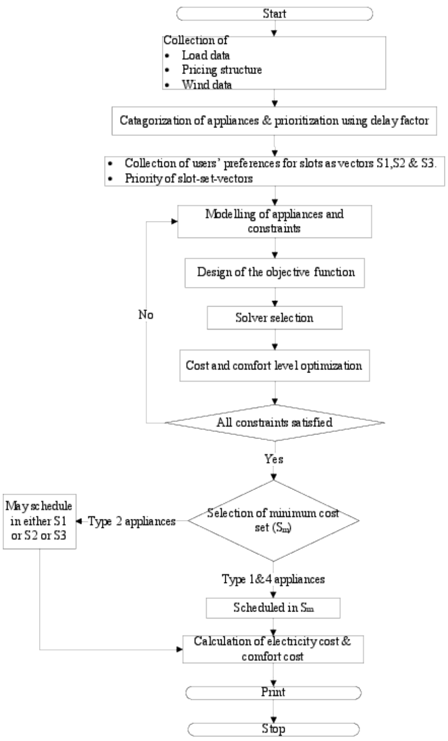

Figure 3. Flowchart of proposed energy scheduling strategy.

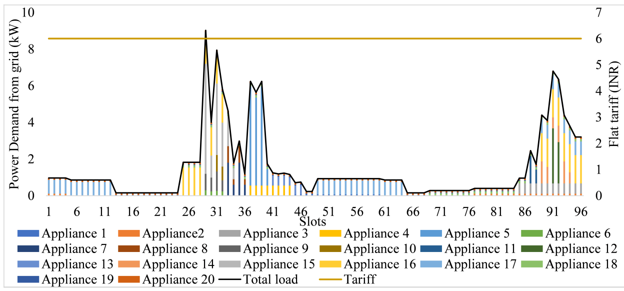

Figure 4. Scheduling of the appliances and overall power demand from the grid for the base case.

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Table 5. Comparative analysis of the scenarios.

Scenario	Q1	Q2	Q	Combined				Relative to the base case	
				Grid power (kW)	Peak power (kW)	Average power (kW)	PAR	Peak	PAR
Base case	881.6	0.0	881.6	146.9	9.02	1.53	5.89	0.0%	0.0%
1	658.2	0.0	658.2	146.9	4.93	1.53	3.22	-45.4%	-45.4%
2	670.4	65.3	735.8	146.9	4.78	1.53	3.13	-47.0%	-47.0%
3	309.3	75.8	385.1	67.0	4.78	0.70	6.86	-47.0%	16.3%
4	98.3	65.3	163.7	18.4	4.62	0.19	24.09	-48.8%	308.7%
5	607.4	146.9	754.3	146.9	4.88	1.53	3.19	-45.9%	-45.9%
6	623.2	0.0	623.2	146.9	4.58	1.53	3.00	-49.2%	-49.2%
7	272.8	76.8	349.5	67.2	4.63	0.70	6.62	-48.7%	12.3%
8	53.4	63.5	116.9	18.4	4.33	0.19	22.59	-52.0%	283.2%
9 S1	599.2	0.0	599.2	146.9	4.85	1.53	3.17	-46.2%	-46.2%
9 S2	591.4	0.0	591.4	146.9	4.88	1.53	3.19	-45.9%	-45.9%
9 S3	578.4	0.0	578.4	146.9	4.88	1.53	3.19	-45.9%	-45.9%
10 S1	603.9	58.6	662.5	146.9	4.93	1.53	3.22	-45.3%	-45.3%
10 S2	600.6	62.8	663.4	146.9	4.98	1.53	3.25	-44.8%	-44.8%
10 S3	586.8	58.1	644.9	146.9	4.99	1.53	3.26	-44.7%	-44.7%
11 S1	194.9	62.7	257.6	48.7	2.92	0.51	5.75	-67.7%	-2.4%
11 S2	197.1	68.4	265.5	50.1	2.68	0.52	5.14	-70.3%	-12.8%
11 S3	199.3	60.8	260.1	51.1	3.02	0.53	5.67	-66.5%	-3.7%
12 S1	31.8	58.6	90.4	18.4	3.59	0.19	18.74	-60.2%	218.0%
12 S2	28.5	62.8	91.3	18.4	3.59	0.19	18.74	-60.2%	218.0%
12 S3	14.7	58.1	72.8	18.4	3.71	0.19	19.33	-58.9%	227.9%
13 S1	553.5	0.0	553.5	146.9	4.96	1.53	3.24	-45.0%	-45.0%
13 S2	551.2	0.0	551.2	146.9	4.76	1.53	3.11	-47.3%	-47.3%
13 S3	539.4	0.0	539.4	146.9	4.88	1.53	3.19	-45.9%	-45.9%
14 S1	558.3	58.4	616.7	146.9	4.97	1.53	3.24	-45.0%	-45.0%
14 S2	558.2	59.8	618.1	146.9	4.79	1.53	3.13	-46.9%	-46.9%
14 S3	549.3	62.4	611.6	146.9	4.67	1.53	3.05	-48.3%	-48.3%
15 S1	171.2	64.6	235.8	47.3	3.15	0.49	6.38	-65.1%	8.2%
15 S2	180.7	80.6	261.3	50.1	2.64	0.52	5.05	-70.8%	-14.3%
15 S3	184.5	61.3	245.8	52.3	2.86	0.55	5.24	-68.3%	-11.0%
16 S1	- 11.5	58.4	46.9	18.4	4.00	0.19	20.85	-55.7%	253.7%
16 S2	- 11.6	59.8	48.3	18.4	3.59	0.19	18.74	-60.2%	218.0%
16 S3	- 20.5	62.4	41.8	18.4	4.27	0.19	22.26	-52.7%	277.7%
			41.8		2.64	1.53			
			Min		Min	Max			

Table 6

A	Set of appliances	$y_{h,n,a}$	Binary variable
N	Number of users or houses	$T_{n,a}$	Total operating time of interruptible loads
H	Set of slots	$S_{h,n,a}$	The binary state vector of an appliance
$F^{h}_{n,a}$	Delay factor	C_h	Tariff rate applied
$W_{n,a}$	Total energy consumption by an appliance	$Q_{n,a}$	Energy consumption vector of an appliance of n^{th} user
W_{max}	Maximum energy consumption in any slot	$P^{h}_{w,n}$	Wind power available for the n^{th} user at slot h
$Y^{max}_{n,a}/Y^{min}_{n,a}$	Maximum/minimum energy level of interruptible loads		

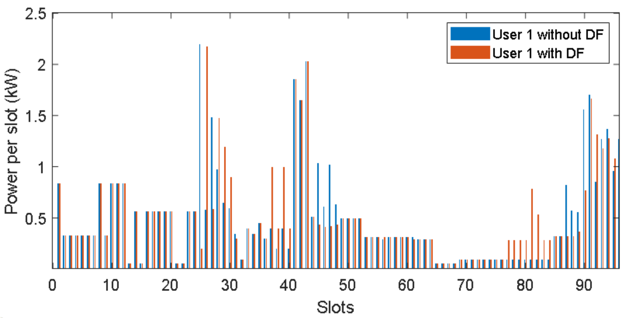

Figure 6. Variation caused by DF in the load curve of user 1.

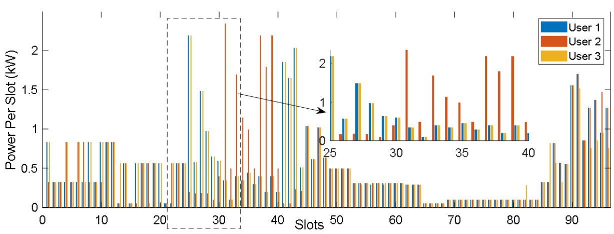

Figure 5. Load curve for users with an RTP tariff structure.

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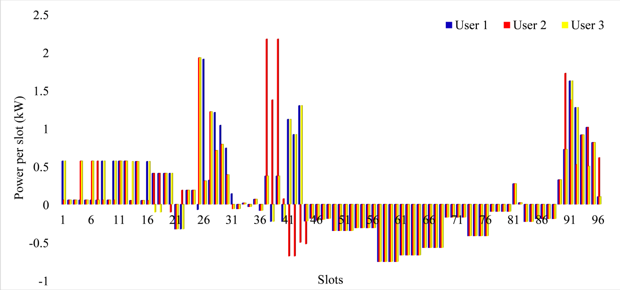

Figure 9. Grid power used by the users with RTP and with DF in bidirectional power-flow mode.

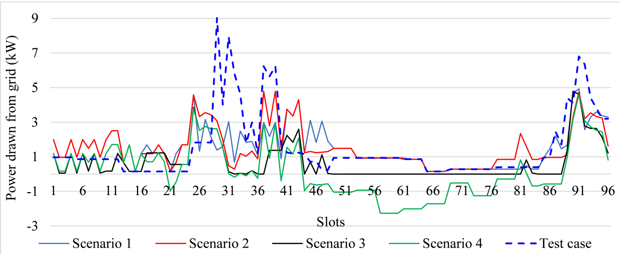

Figure 10. Comparison of the user's collective power consumption from the grid in the base case up to scenario 4.

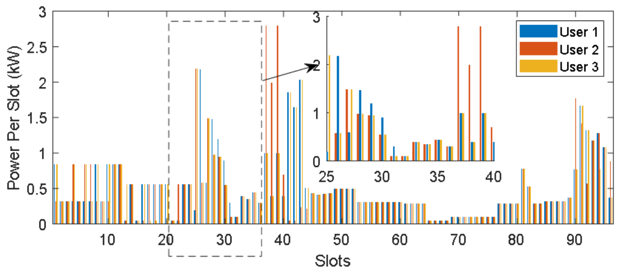

Figure 7. Load curve for users with RTP tariff structure considering DF.

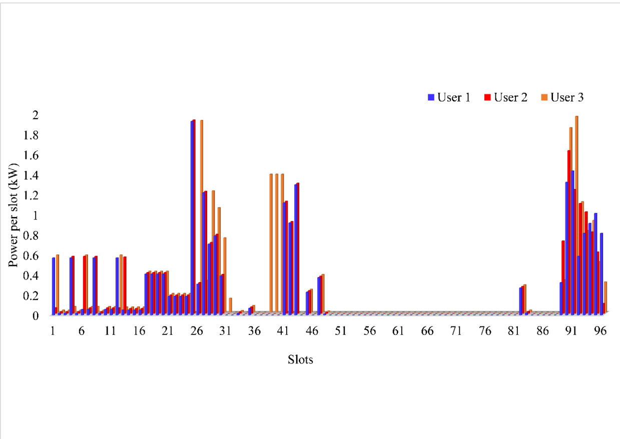

Figure 8. Power demand by the users while implementing RTP with DF in the grid to home (g2h) mode.

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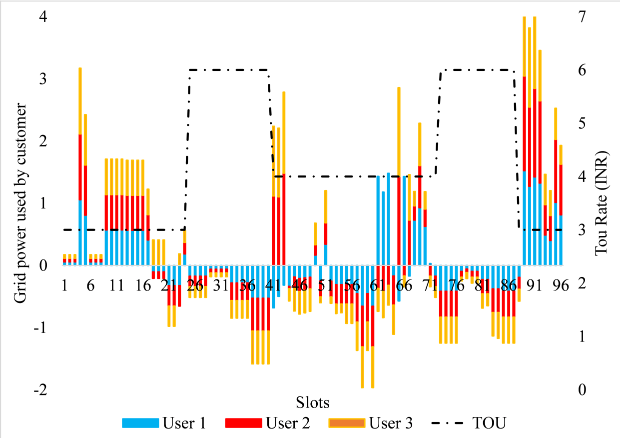

Figure 16. Grid power consumed by users in different time-zone of TOU tariff.